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N/Z effects on ^{40,48}Ca+^{40,48}Ca reactions at 25 MeV/nucleon

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Abstract

Effects related to the neutron to proton ratio (N/Z) degree of freedom in ^{40,48}Ca+^{40,48}Ca reactions at 25 MeV/nucleon have been investigated. Isotopic effect and even-odd staggering characterize the emission of light fragments at forward angles. The study of isobaric ratio ^{7}Li/^{7}Be for quasi-projectile source in semi-peripheral event of reactions allows moreover to investigate isospin diffusion effects in heavy ion collisions.

1 Introduction

In the last two decades, special attention was devoted to study various effects that can be attributed to the neutron to proton ratio (N/Z) degree of freedom in heavy ion collisions, especially in the intermediate energy regime [1]. They go from isotopic effects in the light fragment isotopic yields [2], to isospin transport effects that can be seen in mid-peripheral heavy ion collisions [3]. Also the amplitude of even-odd staggering effect that typically characterize Z and N distributions of light fragments emitted in heavy ion collisions seems to be linked with the neutron content of the entrance channel [4, 5]. Moreover, neutron richness of total system seems to strongly regulate the interplay between various reaction mechanisms that characterize semi-central collisions [7, 8].

To investigate these phenomena, we analyzed experimental results concerning ^{40,48}Ca+^{40,48}Ca reactions at 25 MeV/nucleon. These four reactions are well suited to perform these type of investigations, because of the large variety of N/Z involved in the entrance channels.

The experiment was performed at INFN-LNS SuperConductive Cyclotron facility. ^{40,48}Ca beams were accelerated at 25 MeV/nucleon and impinged on self-supporting ^{40,48}Ca targets. Reaction products were detected by using the 4π multi-detector Chimera [9]. Details about the array and its detection and identification capabilities are described in Refs. [9, 10]; details about data reduction and the selection of complete events can be found in Refs. [8]. Preliminary results are shown in the following sections.

2 Isotopic effects and even-odd staggering

^{40,48}Ca+^{40,48}Ca reactions allow to form intermediate interacting systems with very different neutron richness, going from the symmetric ^{40}Ca+^{40}Ca system, to the very neutron rich ^{48}Ca+^{48}Ca one. For this reason, strong isotopic effects can be recognized in the emission yields of light fragments. In Figure 1 we show the relative emission yields of Carbon isotopes, emitted at forward angles $\theta_{lab} = 9.3°$. We can clearly see that neutron poor isotopes ^{11}C and ^{12}C are more likely emitted in the case of neutron poor ^{40}Ca+^{40}Ca system, while neutron rich ^{13}C and ^{14}C isotopes are emitted with large probability in the case of the very neutron rich ^{48}Ca+^{48}Ca reaction.

It has been noted in literature [4–6] that Z and N distributions of light fragments emitted at forward angles in heavy ion collisions show fine even-odd staggering effects, whose amplitude seems to be correlated to the N/Z of

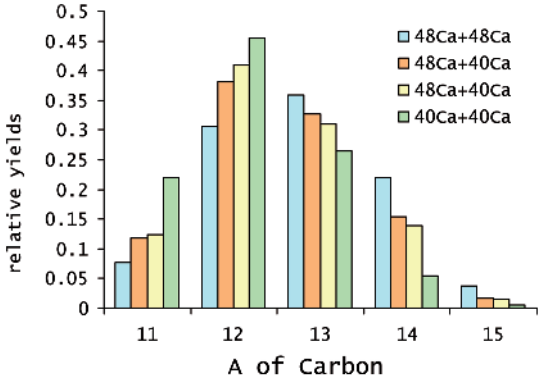

Figure 1: Relative emission yields of Carbon isotopes, emitted at $\overline{\theta_{lab}} = 9.3°$, in the four studied systems ^{40,48}Ca+^{40,48}Ca at 25 MeV/nucleon. Isotopes have been resolved in mass by means of $\Delta E - E$ technique.

entrance channels. Recently, the influence of the particular reaction mechanism (fusion evaporation, deep inelastic, and so on) on even-odd effects have been investigated [4]. We performed also a systematic study on the influence of kinetic energy dissipation on the amplitude of even-odd oscillations. Typically, m_{lcp}, the multiplicity of light charged particles (hydrogens and helions), can be related to the mean excitation energy involved in each event of reaction [11]. We studied Z distributions of light fragments emitted in ^{40}Ca+^{40}Ca events of reaction selected by using various constraints on m_{lcp} ($m_{lcp} \leq 3$, $m_{lcp} \geq 4$ and $m_{lcp} \geq 6$); in Figure 2 we can see that, by increasing the mean m_{lcp}, the amplitude of even-odd staggering effect is more and more softened, and only an extra-production of carbon persists. A similar effect is seen when we select events characterized by heavy residue (HR) emission ($m_1 \geq 46$, m_1 being the mass of the largest fragment emitted).

These preliminary results, in agreement with [4], could be qualitatively explained by considering that even-odd oscillations are fine structure effects mainly related to one-particle separation energy distributions of light fragments; they are then suppressed when the excitation energy involved are too high or when the exit channel involves long decay chains (as in the case of HR emission).

3 Light charged particles in coincidence with HR

An important fraction of the cross-section of semi-central events for the studied systems at 25 MeV/nucleon is due to complete and incomplete fu-

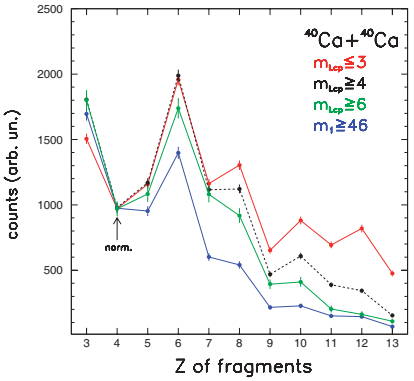

Figure 2: (Color Online) Z distributions of light fragments emitted at $\overline{\theta_{lab}} = 11.5°$ in ^{40}Ca+^{40}Ca events of reaction. Various selections on m_{lcp} have been performed: $m_{lcp} \leq 3$ (red line), $m_{lcp} \geq 4$ (black line) and $m_{lcp} \geq 6$ (green line). HR selection ($m_1 \geq 46$) is in blue.

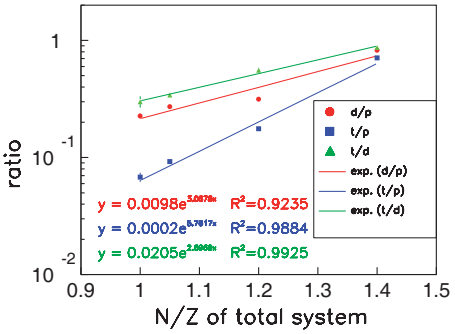

Figure 3: (Color Online) Isotopic ratios d/p, t/p and t/d of hydrogens isotopes emitted in coincidence with HR, in ^{40}Ca+^{40}Ca, ^{40}Ca+^{46}Ti, ^{40}Ca+^{48}Ca and ^{40}Ca+^{48}Ca reactions at 25 MeV/nucleon. Solid lines correspond to exponential fits of experimental distributions.

sion phenomena [12]. It is interesting to investigate if the fusion-like source keeps memory of the N/Z of entrance channel or, in other words, if pre-equilibrium emitted light particles modify the original N/Z rank of the studied systems. In this respect, an indirect way to probe the neutron richness of the fusion-like source can be obtained by studying the neutron content of light particles evaporated by this source [13]. For this reason, we studied the emission of hydrogen isotopes (p,d,t) by fusion-like sources formed in ^{40}Ca+^{40}Ca (N/Z$_{tot}$=1.0), ^{40}Ca+^{46}Ti (N/Z$_{tot}$=1.05), ^{40}Ca+^{48}Ca (N/Z$_{tot}$=1.2) and ^{40}Ca+^{48}Ca (N/Z$_{tot}$=1.4) reactions. First of all, we selected events with HR by imposing $m_1 \geq 0.6 m_{tot}$ (here, m_{tot} is the total mass of the system), i.e. the largest emitted fragment has a mass well larger than the projectile or target one. To avoid contamination due to pre-equilibrium emissions, we discarded light particles emitted at forward angles ($\theta_{cm} \leq 40°$). We performed isotopic ratios d/p, t/p and t/d (n-rich on n-poor isotope) for the selected class of events, and we found the trends shown in Figure 3.

From the figure, it is evident the correlation between the isotopic ratios and the N/Z of the entrance channels. Then, we can infer a strong correlation between the entrance channel N/Z and the neutron content of the fusion-like source; therefore, at these bombarding energies, pre-equilibrium emission does not seem to destroy the original N/Z rank given by the used

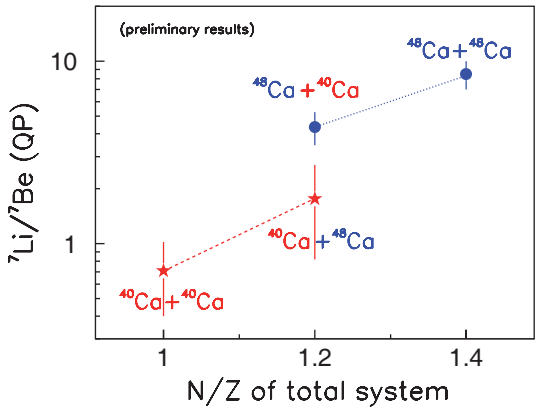

Figure 4: $^{7}Li/^{7}Be$ isobaric ratio of QP sources formed in ^{40,48}Ca+^{40,48}Ca reactions at 25 MeV/nucleon. Lines are only to guide the eye.

entrance channels.

4 Isospin diffusion effects

When semi-peripheral collisions involving projectile and target nuclei with different N/Z take place, a net exchange of neutrons from the neutron rich partner to the neutron poor one can be observed. This effect is often called *isospin diffusion* [3]. It is very interesting to investigate this effect in nuclear reactions around 20 MeV/nucleon; this range of bombarding energies seems to be the best suited to see a transition from a complete charge equilibrium (a behavior typical of low energy deep-inelastic collisions) to an incomplete N/Z sharing, that would lead a non-uniform N/Z distribution in the interacting di-nuclear system [3]. To investigate these phenomena, we need to reconstruct the N/Z content of quasi-projectile (QP), quasi-target and mid-velocity sources, produced in semi-peripheral events. The investigation of $^{7}Li/^{7}Be$ (or other isobaric ratios) represents a possible way to extract information about the neutron richness of a given emitting source [14, 15].

We extracted QP emission yields of ^{7}Li and ^{7}Be for the ^{40,48}Ca+^{40,48}Ca reactions. Obviously, isospin diffusion effects can be seen on the mixed systems ^{40}Ca+^{48}Ca and ^{48}Ca+^{40}Ca, while mass symmetric systems are used as reference points. We extracted isobaric yield ratio by performing a multi-component moving source fit of ^{7}Li and ^{7}Be kinetic energy spectra. To increase the statistics, fit have been performed on inclusive spectra, by taking into account that, for geometrical reasons, inclusive emission is rep-

resentative of semi-peripheral impact parameters. The isobaric ratio for quasi-projectile emission is shown in Figure 4, for the four studied systems (preliminary results), as a function of their total N/Z ratio.

In general, as the total N/Z increases, the QP isobaric ratio also increases. But for the mixed systems (^{40}Ca+^{48}Ca and ^{48}Ca+^{40}Ca), isobaric ratios are different; furthermore, they are correlated to the N/Z of the used projectile. It seems therefore that isospin diffusion takes place, but complete charge equilibrium is not reached at the bombarding energy here used (25 MeV/nucleon).

5 Conclusions

We discuss effects that can be attributed to the N/Z degree of freedom in ^{40,48}Ca+^{40,48}Ca reactions at 25 MeV/nucleon bombarding energies. Isotopic effect has been observed by studying emission yields of carbon isotopes. Effects of excitation energy and reaction mechanisms on even-odd staggering on Z distributions of light fragments have been also investigated. We studied moreover the emission of light charged particles (p,d,t) by fusion-like sources formed in central collisions; it seems that pre-equilibrium emitted particles do not modify the original N/Z rank given by the neutron excess of the entrance channel. Finally, we investigated isospin diffusion effect in semi-peripheral collision, and we found that, at this bombarding energy, a complete charge equilibrium in the di-nuclear interacting system is not achieved.

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